

## Infrared Camera Characterization of Bi-Propellant Reaction Control Engines During Auxiliary Propulsion Systems Tests at NASA's White Sands Test Facility In Las Cruces, New Mexico

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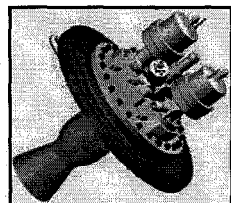
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### ABSTRACT

This paper describes the application of a FLIR Systems A40M infrared (IR) digital camera for thermal monitoring of a Liquid Oxygen (LOX) and Ethanol bi-propellant Reaction Control Engine (RCE) during Auxiliary Propulsion System (APS) testing at the National Aeronautics & Space Administration's (NASA) White Sands Test Facility (WSTF) near Las Cruces, New Mexico. Typically, NASA has relied mostly on the use of ThermoCouples (TC) for this type of thermal monitoring due to the variability of constraints required to accurately map rapidly changing temperatures from ambient to glowing hot chamber material. Obtaining accurate real-time temperatures in the IR spectrum is made even more elusive by the changing emissivity of the chamber material as it begins to glow. The parameters evaluated prior to APS testing included: (1) remote operation of the A40M camera using fiber optic Firewire signal sender and receiver units; (2) operation of the camera inside a Pelco explosion proof enclosure with a germanium window; (3) remote analog signal display for real-time monitoring; (4) remote digital data acquisition of the A40M's sensor information using FLIR's ThermoCAM Researcher Pro 2.8 software; and (5) overall reliability of the system. An initial characterization report was prepared after the A40M characterization tests at Marshall Space Flight Center (MSFC) to document controlled heat source comparisons to calibrated TCs. Summary IR digital data recorded from WSTF's APS testing is included within this document along with findings, lessons learned, and recommendations for further usage as a monitoring tool for the development of rocket engines.

### INTRODUCTION & BACKGROUND

#### Approach



Development work into the LOX/Ethanol RCEs began as part of NASA's Next Generation Launch Technology (NGLT) program to advance the development of non-toxic thruster rocket engines. The bi-propellant engines in development provided 870 pounds of thrust during testing. The Reaction Control Engines (RCE) were capable of operating in both steady-state and pulse-mode operation – the engines are fired on and off repeatedly to achieve a required duty cycle to accommodate Guidance Navigation and Control (GN&C) metrics for spacecraft operation. This particular RCE operates at temperatures normally between 2000-2500 degrees Fahrenheit. If there is an excursion of the mixture ratio

between the two propellants, the temperatures can exceed the nominal operating temperatures and protective coatings applied to the RCE chamber and nozzle can quickly become damaged. Once the protective coating is damaged, hot-gas burn-through of the chamber and nozzle material is possible within just a few seconds. Therefore, it is critical that temperatures of chamber and nozzle areas are monitored during hot-fire tests to insure safety to test articles, facility, and test personnel in the area.

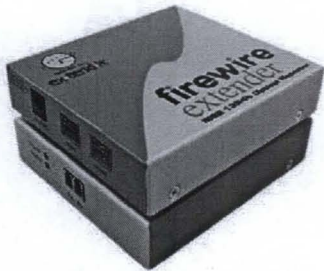
After several months of exhausting hot-fire engine tests, the team became frustrated with the frequent occurrence of TC wires breaking during pulse-mode operation. Once the TCs were out of service, the ability to monitor the RCE was limited to the remainder of TCs functioning within the usual grid of 32 TCs welded to the chamber.

A thermography solution appeared on our horizon once we discussed the possibility of using an IR camera with our local FLIR technical representatives. Surprisingly, thermography is considered a relatively new application for most rocket engine test facilities. Most instrumentation engineers that we work with have traditionally preferred only TCs for monitoring test articles such as rocket engines since the emissivity changes rapidly as they heat up causing anomalous temperature results and their benefit was mostly considered supplemental and usually only for mapping thermal gradients for trending and possible TC placement.

MSFC purchased a FLIR A40M IR camera in early 2005 and in time to utilize it for thermal characterizations of sea-level Acceptance Test Procedure (ATP) at our contractor's facility in California. This particular site posed a

significant challenge to personnel because the test stand was located approximately 300 feet from the control room. Since the A40M camera can transmit approximately 10 megabytes per second to a computer's hard-drive, our only option was to use a fiber optic line in conjunction with a Firewire repeater/multiplexer from Gefen to accomplish this remote operation of the A40M from the control room. The Gefen unit was recommended to MSFC by FLIR technical personnel. The following table is a listing of the Original Equipment Manufacturer's (OEM) items we used to accomplish this setup:

Item	Qty.	Description
1	1	FLIR Systems A40M Researcher IR camera with supplied power supply.
2	1	FLIR Systems 2x telephoto lens for the A40M Researcher IR camera.
3	1	ThermaCAM Researcher Professional 2.8 IR software.
4	1	Dell D600 notebook computer with 6 pin Firewire PCMCIA adapter card; 1 GB Memory ;60 GB Hard-drive
5	1	L-Com 100 meter LC to LC 62.5/125 micron fiber optic cable.
6	1	Gefen Firewire sender unit with 12 Volts DC 3.0 amp power supply
7	1	Gefen Firewire receiver unit with 12 VDC 3.0 amp power supply
8	2	Gefen supplied 6 pin male connector (both ends) Firewire cable.
9	1	FLIR Systems supplied 6 pin male connector (both ends) Firewire cable



**Figure 1.** Gefen 800 Firewire Extender.



**Figure 2.** FLIR Systems A40M IR Camera.

## THRUSTER VENDOR TESTING

### Initial Approach

This system was ready for ATP hot-fire thermal characterizations during March and April of 2005. Setup of the A40M with the Gefen Firewire extender units proved to be rather straightforward. However, after connections were achieved and testing began, signal losses proved troublesome. Several thermal data acquisitions were achieved during the first series of tests. Later tests were interrupted due to more frequent signal losses. Personnel inspected all of the Firewire and fiber connections along with lines to insure that physical disconnects or damage was not the root cause. We ended ATP testing in California with marginal results from the system.

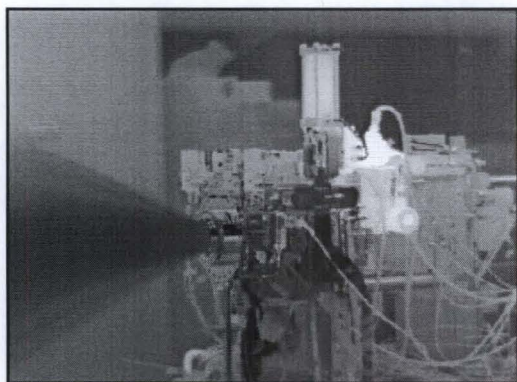
After the California setup was duplicated in the lab at MSFC, it was determined that the Gefen sender unit failed early causing the Firewire signal issues. We generally suspected that overpressure from the thruster pulsing caused the failure of the Gefen sender unit, but it could also have been an infant mortality issue with the hardware.

The data correlation between the TC and A40M camera varied somewhat during the hot-fire tests. Several charts were generated to align the TC data to that of the ThermaCAM Researcher Pro 2.8 sequence files.

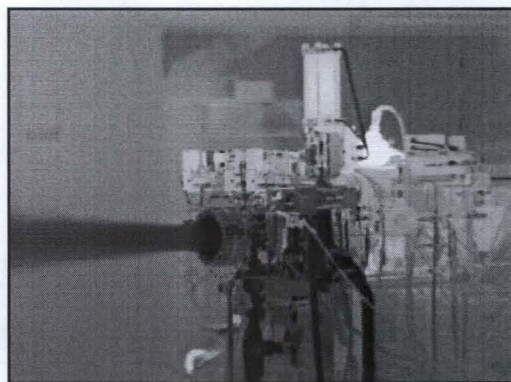
At the close of each test day, personnel secured the FLIR camera equipment and validated its operation prior to engine tests. Cold-flow Tests 35-40 were recorded along with the first hot-fire Test 101. Figures 3 & 4 on the following page are representative of the imagery generated by the FLIR Systems camera during this day. Further detailed evaluation of the thruster vendor's thermocouple data to our FLIR sequence files still needed to occur, but it



appeared during test that the two various types of instrumentation matched closely with each other. The infrared sensor is limited to  $-45^{\circ}\text{F}$  as indicated by the dark shades of the cryogen supply lines to the injector.



**Figure 3.**  
Fuel cold-flow Test 30, 1.25 sec. test.



**Figure 4.**  
LOX cold-flow Test 34, 15 sec. test.

## **Monday, March 28, 2005** **Hot-fire Tests 124-131**

The following tests provided a mix of both steady state hot-fire tests along with a few pulsed hot-fire tests.

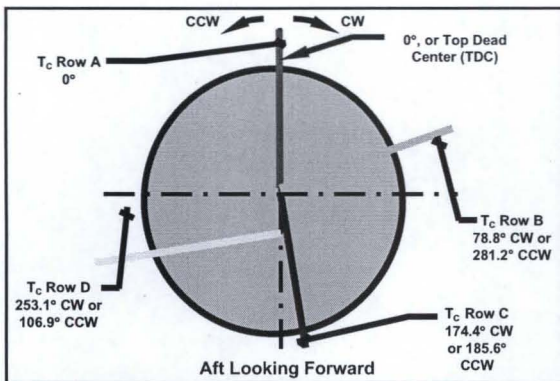
The WinPlot traces are shown in degrees Rankine (Fahrenheit  $\approx 460^{\circ}$ ) and the FLIR print screen images are shown using degrees Fahrenheit since Rankine is not an option within the software.

Test 124 was used to compare data recorded by the FLIR Systems A40M infrared camera using the ThermoCAM Researcher Pro 2.8 software to that of the vendor's Data Control Acquisition System (DCAS) using Winplot. Test 124 was a 60 second steady-state hot-fire test. The thermal data shown in Figures 5-8 represent the time just prior to the main valves being powered "off". The Winplot traces, Figure 8, from the thruster vendor thermocouple data represent the time duration for the entire test, but the temperatures are mostly constant within a horizontal band by thermocouple location. The maximum temperature from the thruster vendor's data from Thermocouple 7D indicates a temperature of  $2450^{\circ}\text{Rankine}$  whereas the maximum temperature from the A40M infrared camera LI01 indicates  $2462^{\circ}\text{Rankine}$  or  $2002^{\circ}\text{Fahrenheit}$ . The temperature slope of LI02 from the A40M infrared camera appears consistent with the temperature slope recorded by the thruster vendor thermocouples.

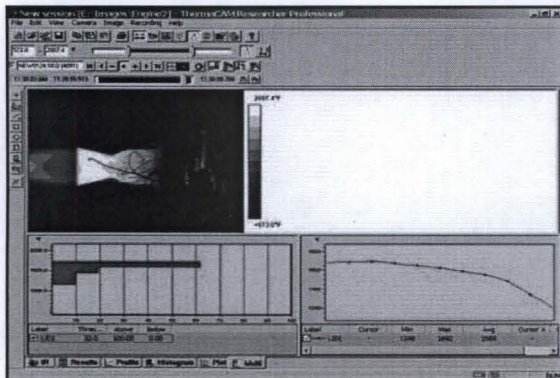
Figures 7 & 8 indicate parallel trending for the heat affected zones where the main chamber thermocouples are located to the FLIR A40M camera data displayed within the ThermoCAM Researcher Pro 2.8 screen. Axial locations 4 to 5 are represented. Again, the thruster vendor data shown with the WinPlot traces is shown in degrees Rankine (Fahrenheit  $\approx 460$ ) and the ThermoCAM Researcher Pro 2.8 traces are shown in degrees Fahrenheit.

The infrared pallet shown in Figure 12 is optimized for visual clarity specific to the heat affected zones and features discussed within the text of this document. Generally, Rainbow10, Gray10, and Iron10 are best suited for visually defining heat affected zones without utilizing the excessive gradation of tone commonly seen in images such as with Figures 9-12. The ability of the FLIR A40M camera to capture the total seamless radiometric signature of the RCE main chamber during hot-fire testing is perhaps best exemplified within Figures 9-12. While associated mainly with heat radiation, they do have some properties which are the same as those of visible light.<sup>1</sup>

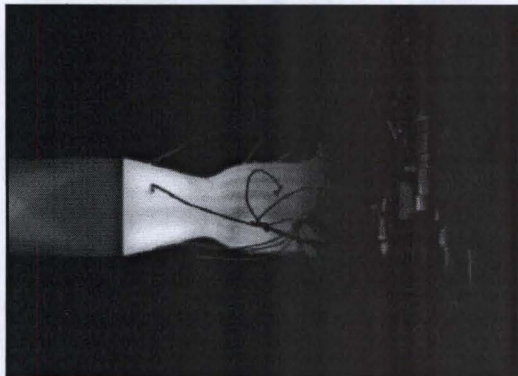




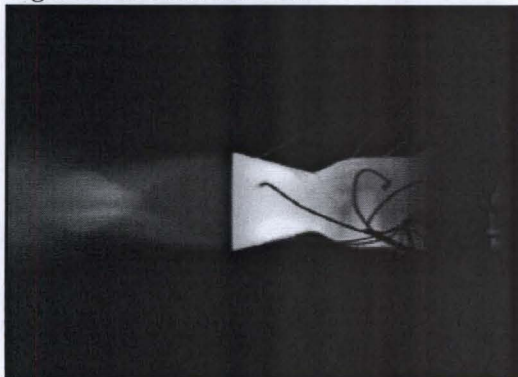
**Figure 5.** ATP thermocouple location section.



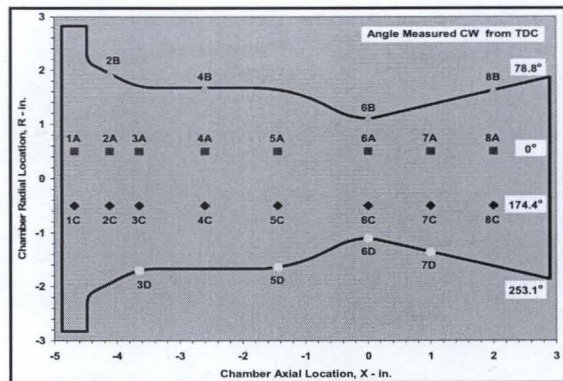
**Figure 7. ThermaCAM Researcher Pro 2.8.**



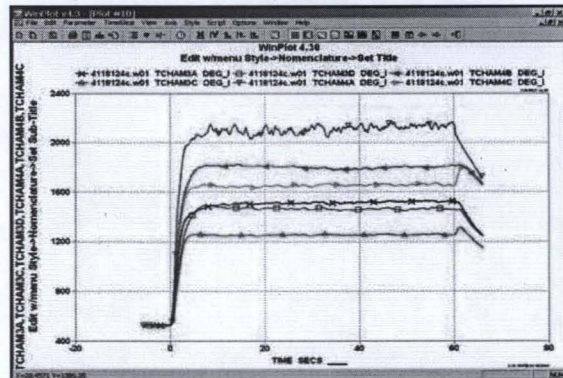
**Figure 9. Hot-fire Test 124.**



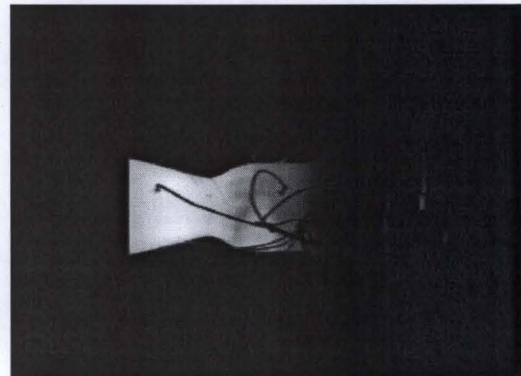
**Figure 11. Hot-fire Test 131 pulse @ max press.**



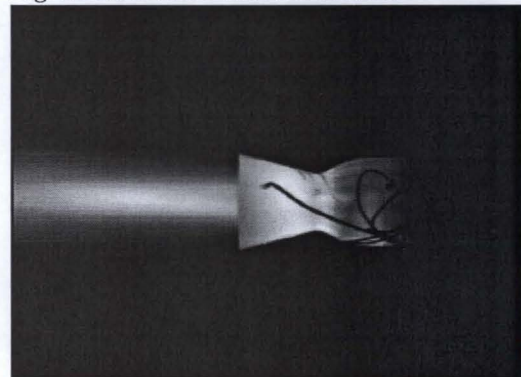
**Figure 6.** ATP thermocouple location diagram.



**Figure 8.** WinPlot traces.



**Figure 10. Hot-fire Test 125 soak-out.**



**Figure 12.** Hot-Fire Test 131 post pulse abating.



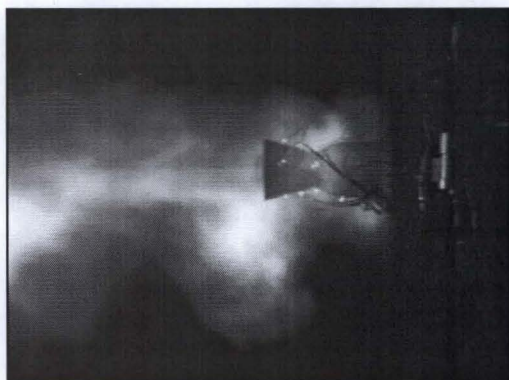
Thursday, April 7, 2005

## Hot-fire Tests 149-156

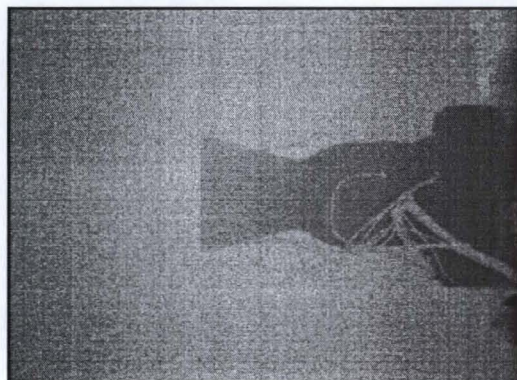
The Thursday morning tests were conducted using a co-located Dell notebook to acquire the infrared data.

**Figure 13.** This IR imagery indicates the ignition of pooled propellant (hot gas) as the result of a previous non-ignition. The ignition occurred after the propellant was expelled from the chamber and ignited by the subsequent pulse.

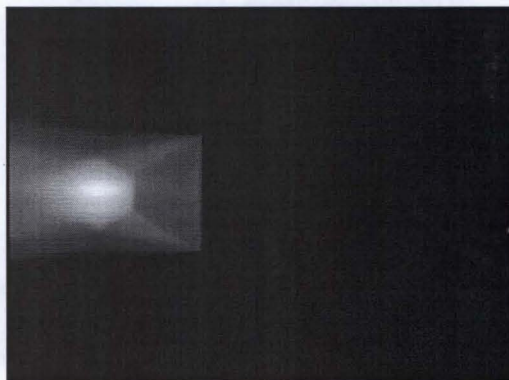
**Figures 14-17.** In the following figures, the first 4 frames of the 5 second pre-burn are shown. The images were recorded at 7.5 frames per second. In Figure 15 the rocket plume is imaged within the calibrated scale of the camera +572° Fahrenheit. The main chamber heating is not visible until the second frame in Figure 16. In Figure 17, the radial Fuel Film Cooling (FFC) pattern is easily seen upstream of the throat section.



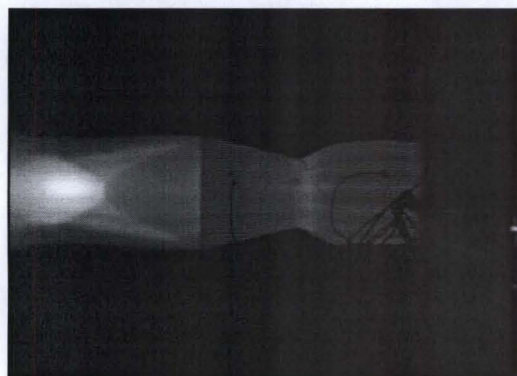
**Figure 13.** Hot gas from a previous non-ignition.



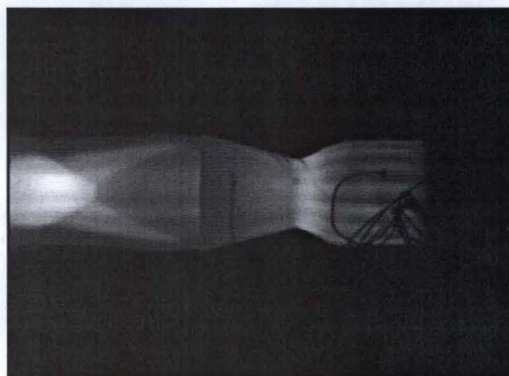
**Figure 14.** Test 151 pre-pulse.



**Figure 15.** Test 151 Pulse one frame one.



**Figure 16.** Test 151 pulse one frame two.



**Figure 17.** Test 151 pulse one frame three.

**Figure 18.** Within FLIR Systems ThermaCAM Researcher Pro 2.8, it is possible to export live data to Excel. The image on the following page is representative of that capability.



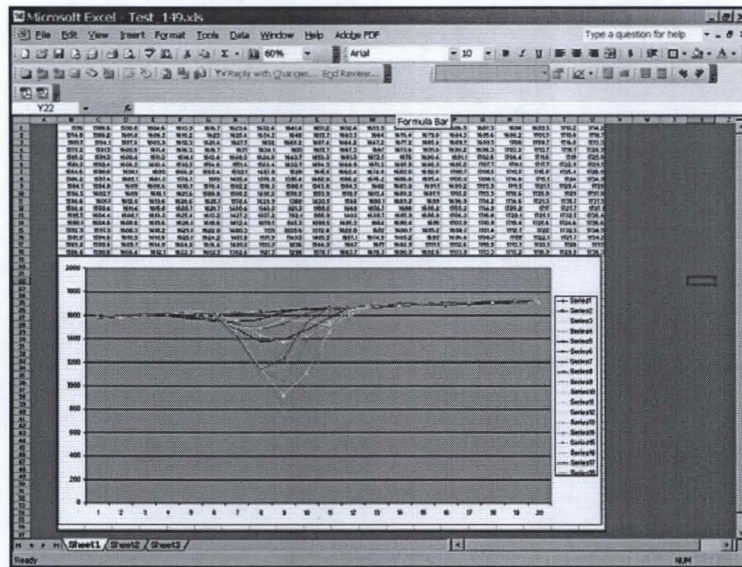


Figure 18. Screen capture from FLIR sequence file to Excel.

## Conclusions

The earlier concerns that the FLIR Systems A40M IR camera was measuring higher temperatures than those indicated by the instrumented Type K thermocouples, which were welded onto the RCE chamber during ATP, has been somewhat alleviated by the Hardware In-The-Loop (HIL) tests performed previously at the MSFC Valve Shop. The camera's temperature bandwidth of 1750°F to 2732°F with red to white glowing metal appears to have an emissivity asymptotical to 1.0, thereby, reducing the amount of uncertainty associated with emissivity drift since this noted temperature interval is within the temperature range of most concern during the hot-fire test sequences.

There was still concern regarding the robustness of the Firewire extender hardware purchased from Gefen. A replacement unit along with a backup unit was ordered and received by MSFC.

## VALVE SHOP CHARACTERIZATION

### Objective

The objective for the FLIR Systems A40M IR Camera HIL Tests was primarily to validate the accuracy of the camera to the standard reference Type K TCs planned for use at WSTF during APS testing. This was the first opportunity to test the A40M IR camera within the Pelco explosion-proof enclosure illustrated in Figure 19. A Germanium lens was used to ensure that the camera could detect heat outside of the enclosure while remaining protected inside the enclosure. Heat sources utilized included: electric heat gun, propane torch, map torch, and oxygen acetylene torch as shown being used in Figure 20.

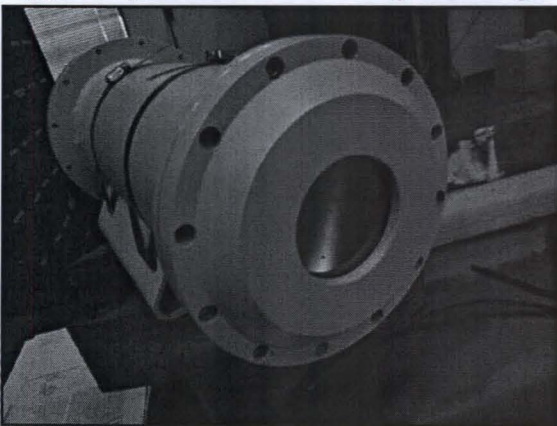


Figure 19. Pelco enclosure with Germanium lens installed.



Figure 20. Heat being applied to instrumented panel.





**Figure 21.** Typical setup from Sequence Tests 30-35 using the Pelco enclosure.

## **Approach**

The approach/agenda was originally scheduled to occur at the MSFC Components Development Area (CDA). However, scheduling conflicts prevented this and the tests were moved to the MSFC Valve Shop. Before leaving the original setup area at the CDA, we confirmed that the Gefen sender amplifier unit used during ATP at the thruster vendor was nonfunctional. The determination of this nonfunctional key component was instrumental to understanding why intermittent remote disconnects occurred to the camera from the control room prior to the Firewire system failing completely.

## **IR Camera to Thermocouple Comparisons**

### **Sequence Test 34**

Sequence Test 34 involved both IR and analog thermocouple data recordings. The comparisons below are representative of how the IR thermography compares with the analog thermocouple data.

The temperature goal for this test was 1750°F. The general thermocouple arrangement is represented by the ThermoCAM Researcher Pro 2.8 screen as shown in Figure 22. Figure 24 contains the analog thermocouple data of 1742°F from Thermocouple 3 during the same time frame as Figure 23 from the IR screen. The string data exported from the ThermoCAM program is represented in the tabular data shown in Figure 25 which is representative of the pixel arrangement contained within the white-bordered box in Figure 23.

From the afore-mentioned figures, the alignment of the analog thermocouple data to that of the IR data is easily recognizable. This example is also true for other Sequence Tests where the stainless steel begins to glow from the torch's applied heat.

There are other temperature variances and issues of uncertainty that can be further elaborated upon in successive tests, but for purposes of this report; the validation of traditional thermocouple analog data to that of the IR digital data is confirmed.

## **IR Camera Setup Reliability History**

Earlier in ATP testing on March 17, 2005 at the thruster vendor, there was a problem receiving and transmitting the digital signal through the Firewire connection. The thruster vendor mentioned how two notebooks were previously damaged during another program when they were located in the same test cell. Several methods to reactivate the signal at the time were attempted, but none were successful. The only recourse during these tests was to locate one of the notebook computers near the test cell and bypass the optical Firewire extender completely. This technique of activating the A40M locally at the test cell proved successful, but extremely labor intensive since it involved separate trips back and forth to the test cell from the control room prior to and following each successful and aborted test.

Prior to the IR camera thermocouple characterization tests, we tested the Gefen sender and receiver units and determined that the sender unit used in the test cell was non-functional. The root cause of the Gefen sender unit failure during ATP is unknown, but the overpressure from the engine pulsing is a credible cause.



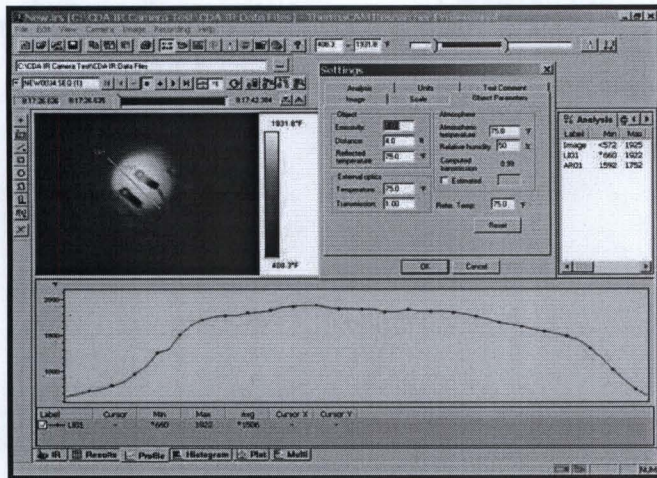


Figure 22. ThermoCAM screen image.

1615.4	1692.7	1618.3	1609.5	1615.4	1617.4
1603.9	1710.8	1722	1699.6	1678.6	1615.7
1647.4	1742.9	1751.7	1733.7	1654.4	1616.6
1717.7	1742	1746.5	1721.8	1592.2	1604.8
1631.6	1612.6	1644.7	1704.7	1612.7	1606.5
1593.2	1606.8	1610.9	1630.1	1610.6	1624.2

Figure 25. Tabular IR string data from area analysis on Thermocouple 3.

## Conclusions

The earlier concerns that the FLIR Systems A40M IR camera was measuring temperatures higher than those indicated by the instrumented Type K thermocouples welded onto the RCE chamber during ATP has been somewhat alleviated by the HIL tests performed during this past July at the MSFC Valve Shop. The camera's temperature bandwidth of 1750°F to 2732°F with red to yellow glowing metal seems to become asymptotical to 1.0, thereby, reducing the amount of uncertainty associated with emissivity drift since this noted temperature interval is within the temperature range of most concern during the hot-fire test sequences.

Figure 26. Derived uncertainty from thruster vendor tests.

Variance Source	Known Variance ≈ ± °F	Known Variance ≈ ± °F
Thermocouple Bead (By Vendor Analysis)	90	90
Nozzle Section (By IR Data Review)	50	50
Combustion Chamber Section (By IR Data Review)	250	250

	TC 6-8 Temperature °F	TC 1-5 Temperature °F
Maximum TC Test 127 High PC/MR	2048	1767
Maximum IR Test 127 High PC/MR $\epsilon = 0.92$	2256	1845

	Thermocouples	Thermocouples
Max Temperature $\Sigma$ Variance Potential (TC)	2388	2107

In-Range Delta IR versus TC Including Summed Variance Sources	132	262
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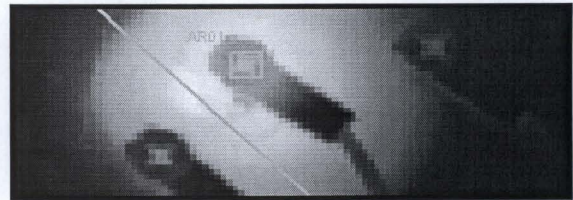


Figure 23. Enlarged Thermocouple analysis area.

PI_T_3
Deg_F
Plate_Temperature_3
PI_T_3
1742.6
1742.5
1742.5
1742.5
1742.5

Figure 24. Thermocouple 3 data from CSV file.



Some concern remained regarding the robustness of the Firewire extender hardware purchased from Gefen. The concern was mostly from the Gefen sender unit failure from noise induced vibration during ATP tests. Replacement Gefen sender and receiver units, along with one backup Gefen sender and receiver, were previously ordered and received by MSFC. In the event that either or both of the Gefen sender or receiver units failed during APS test at WSTF, the spare units could have been replaced easily between tests. The Gefen sender unit was installed into the Pelco explosion-proof enclosure, reducing the likelihood of failure from noise induced vibration. During the camera characterization tests at the MSFC Valve Shop, the signal connections through the Gefen Firewire system from the camera to the notebook running the ThermaCAM Researcher Pro 2.8 software performed without fault; although, the connection confirmation was unpredictably slow at times.

After the IR camera characterization tests were complete, two other tests were performed. The first of these tests involved running both the IR camera and Gefen Firewire sender unit inside the sealed Pelco enclosure without a purge to determine how the components would affect the internal temperature within the Pelco enclosure. This test resulted in a 0.8°F temperature rise within the enclosure over a 30 minute period of time or a 1.6°F rise per hour. The second post camera characterization test performed slowly and increased the internal chamber pressure of the Pelco enclosure up to 12.5 psi over atmosphere. This 12.5 psi change in pressure was required to validate that the Germanium lens would survive the worst case scenario at WSTF while being operated within the TS401 altitude chamber.

Following this series of IR camera tests at the MSFC Valve Shop, the components were crated and packaged by NASA personnel at the MSFC CDA and shipped to WSTF. A thorough checkout of the assembled IR camera components at WSTF prior to cold-flow testing of the APS system was performed to insure that the complete system functioned properly during the critical hot-fire tests that followed.

## Recommendations and Observations

The following recommendations were given prior to WSTF testing:

*Hardware in-the-loop testing at MSFC's Component Development Area (CDA) should resolve all of the issues associated with the robustness, reliability, and accuracy of the FLIR Systems infrared camera. This type of bench testing should have occurred prior to taking the system to the thruster vendor for the ATP of the three WSTF RCEs, but there was not sufficient time due to last-minute Gefen component arrivals prior to ATP for a proper MSFC system validation.*

*It is essential that we conduct a complete hardware in-the-loop test of the infrared thermography system prior to installing the components at WSTF. This system level test needs to include the setup of the A40M camera into the actual Pelco explosion proof enclosure planned for use in WSTF's Test Cell 401.*

These July 2005 HIL tests have addressed all of the issues noted in the above mentioned paragraphs. More time could have been used testing the thermography to instrumented thermocouples, but at this time enough knowledge had been attained regarding the A40M's operation to confidently go into APS testing at WSTF.

One product of this report is a checklist for setting up the A40M IR camera. This checklist served as a guideline for getting the most accurate thermography possible given the limited access of Test Stand 401 at WSTF and the Field Of View (FOV) constraints of the instrumented RCE chambers.

The minimum gaseous nitrogen purge rate can adjust down from the current 5 scfm to 1 scfm based on the last thermal Soakout tests conducted at the MSFC Valve Shop with the assembled IR camera components inside the sealed Pelco enclosure.



Figure 27. Pressure test with Kellum tether.

## WSTF Testing

### Problem Statement

- WSTF required Pelco or equivalent explosion proof enclosures for electronics operated within TS401.
- Pelco did not offer an IR compatible optic lens for use with their hermetically sealed, or airtight, explosion proof camera enclosures.
- The sealed Pelco enclosure requires a minimum airflow to maintain OEM operational temperature limits for both the A40M and Gefen sender unit.
- Real-time temperature calibrated adjustments at altitude are necessary through the Pelco IR optic to establish confidence of the output among the test team personnel.
- Expected chamber emissivity variance during test of  $\approx 0.65$  to 1.00.
- Entry into TS401 during test operations was not an option for making adjustments to the IR camera setup.
- Dynamic pressure variance discovered just prior to test exceeded earlier proof pressure validation.

### Test Cell 401 Description

"The test stand was originally designed to test the full-scale Apollo Lunar Excursion Module (ascent and descent stages) in a simulated space environment. Since the Apollo program, the stand has been used to test a wide variety of hypergolic and nontoxic engines, systems, components, and limited small solid rocket motors.

The vacuum cell is a 10 m-diameter by 11.6 m-high carbon-steel chamber, designed to accommodate an engine with a mated test rig for propulsion systems testing. This provides three interior working levels and a test article envelope of approximately 5 m by 5 m by 6.5 m tall. A cell extension can be added to increase the available test article height to 12.6 m. The cell lid is removable for insertion of large test articles. Smaller test articles are inserted through the 2 m by 2.5 m door located on the grade deck of the test stand.

The altitude chamber allows engine-firing tests at simulated altitude or ambient conditions. The cell is capable of providing either a simulated altitude environment (approximately 37 km), or an ambient pressure environment (632 torr), and can be used to test complete upper stages in the 100 kN thrust-class range.

Test Stand 401 has an environmental conditioning system capable of maintaining interior and test article temperatures from 5–50 °C while at ambient pressure. Heat capacity of the insulated vacuum cell and associated structure is normally sufficient to maintain thermal control in this range during short tests. Limited thermal control during altitude tests may be accomplished by using portable cryogenic panels, warm or cold spot purges, or electric lights or contact heaters."<sup>2</sup>

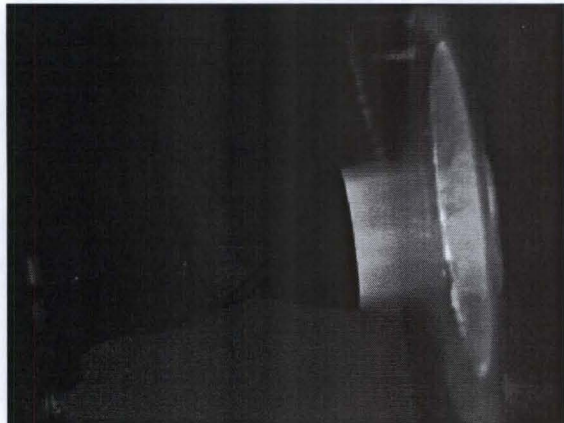
### Description of the A40M IR Camera WSTF Installation

The A40M camera (inside the sealed Pelco enclosure) was either mounted to a motorized articulating base or to a static tripod during test operations. The A40M was mounted to the same slider used during MSFC CDA setup. The Gefen sender unit was also located within the Pelco enclosure. A Firewire was used to connect data between the A40M and the Gefen sender unit. An 18" LC/LC connectorized fiberoptic cable was used to transfer the multiplexed signal from the Gefen sender to the facility fiberoptic cable used between TS401 and the 400 Area Control Room. A Minco electrometric feed through, part number AC3015H4V100, was used to seal the penetration of the fiberoptic cable in the Pelco's aft flange cover. Hermetically sealed military standard electrical connectors were used to transfer power to the inside of the Pelco enclosure. Two 12 VDC power converters were used within the Pelco enclosure to provide power to both the A40M and Gefen sender unit. A surface mounted TC was applied to the inner plane of the Pelco's IR optic to accommodate an active secondary optic temperature input to the A40M's processor. The distance between the test cell and the control room was approximately 500' and required a pre-assembled off-the-shelf 200 meter fiber optic cable for the connection.

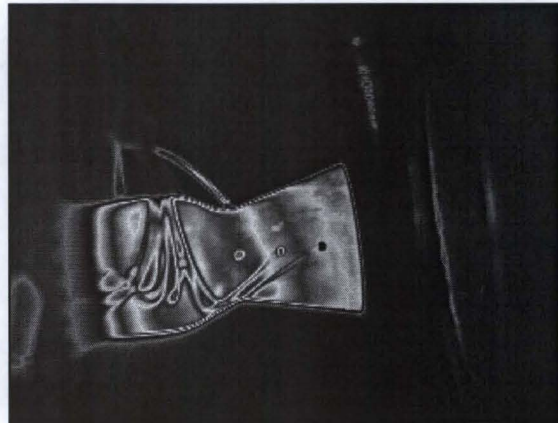
Each morning before testing began, personnel recorded ambient test cell temperature, humidity, reflected temperature (radiance), along with several active TC spot measurements to IR output indicated within the ThermoCAM Researcher Pro 2.8 software. The camera's FOV was also addressed each morning specific to each day's planned tests to insure the proper capture of thermal data.



The following A40M images are representative of the final WSTF APS LOX/Ethanol hot-fire engine tests:



**Figure 28.** Initial pulse before chamber heating.



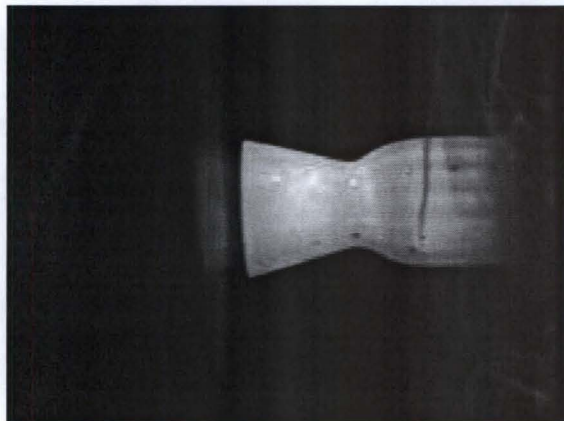
**Figure 29.** Thermal Soakout during coast period.



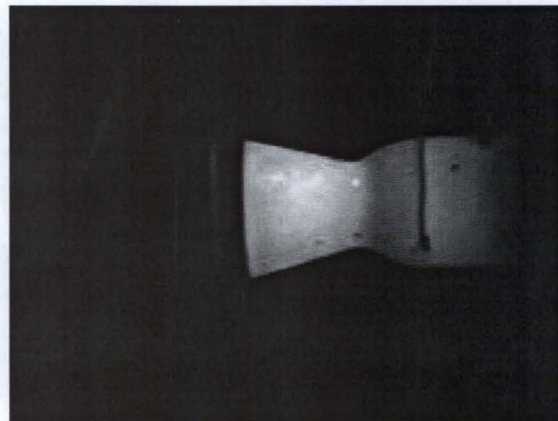
**Figure 30.** Screen-shot of sequenced engine firings.



**Figure 31.** Simultaneous hot-fire at vacuum.



**Figure 32.** Normal hot-fire pulse.



**Figure 33.** Missed ignition/cold chamber.

## Conclusions

- The FLIR A40M IR camera and MSFC sponsored set-up validated the usefulness of thermography as a tool to enhance thermal characterization of hot-fire thruster vacuum chamber tests at WSTF.
- The FLIR A40M IR camera required pre-test characterization with a representative thermal target.
- The FLIR A40M IR camera required calibrated thermocouples within key areas of the FOV to maintain the confidence level of test personnel who relied on the images to make quick dispositions during test operations.
- Unplanned usage (detection of non-ignitions during pulsed mode operations).
- The FLIR A40M IR camera was a minor expense compared to overall test budget.
- The thermography images created by the thermography setup were useful to the project office as a communication tool.
- Original expectations involved a rather simple tripod reposition of the A40M camera; however, since the tripod required clips to anchor it to the test cell floor grating, this repositioning task became much more time consuming than originally planned. Once testing began each morning, we were limited to that position for the remainder of the day. For future tests, multiple IR cameras are recommended to optimize target opportunities.

## Recommendations

- Use of a ruggedized Firewire sender/amplifier unit is highly recommended if the Firewire interface continues as the only high speed data interface between the camera and ThermoCAM Researcher Pro software.
- Radiation from real surfaces differs in several aspects from blackbody radiation.<sup>3</sup> Therefore, pre-test characterization of the IR camera setup in a controlled environment under simulated expected test conditions is recommended to minimize the test site setup and dial-in time for the camera's object parameters.
- For FLIR to add a Rankine unit of measurement to the ThermoCam Researcher Pro software.
- For FLIR to add an LC fiber optic connection to their A40M interface connect panel to avoid the use of a Firewire multiplexer/amplifier/sender interface.
- For Pelco to add a IR compatible structural window as an option to their EHX explosion-proof camera enclosure product line.

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